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Davis et al.

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(54) **MAGNETIC LEVITATION APPARATUS**

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(73) Assignee: **Levitation Arts Inc.**

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H02K 41/00 (2006.01)
H02K 7/09 (2006.01)
H02K 13/08 (2006.01)

(52) **U.S. Cl.** **310/12**; 310/90.5; 104/284

(58) **Field of Classification Search** 310/12–14, 310/90.5; 104/284
See application file for complete search history.

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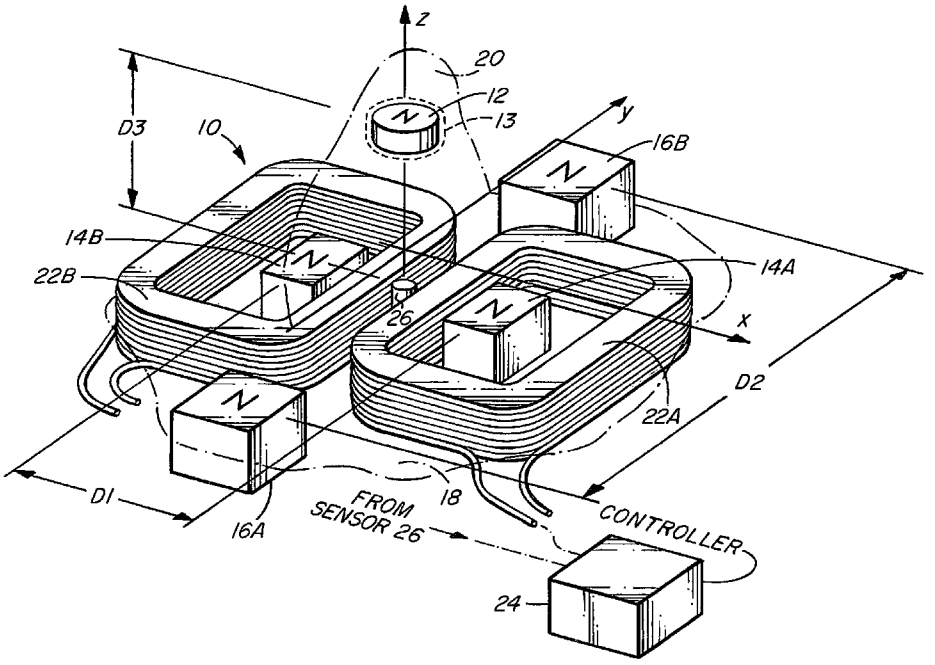
Primary Examiner—Karl Tamai
Assistant Examiner—David W. Scheuermann

(57) **ABSTRACT**

A magnetic levitation apparatus supports a magnetic element in a magnetic field. A control system controls a variable magnetic field to maintain the magnetic element at an equilibrium location relative to an unstable axis. In some embodiments the variable magnetic field has a gradient in the direction of the unstable axis but no field component. In some embodiments the magnetic field is provided by an array of four discrete magnets. In some embodiments additional magnets provide increased field intensity at the equilibrium location this increases stability of the levitated magnetic element against overturning. Light and electrical power may be supplied to the levitating magnetic element.

39 Claims, 9 Drawing Sheets



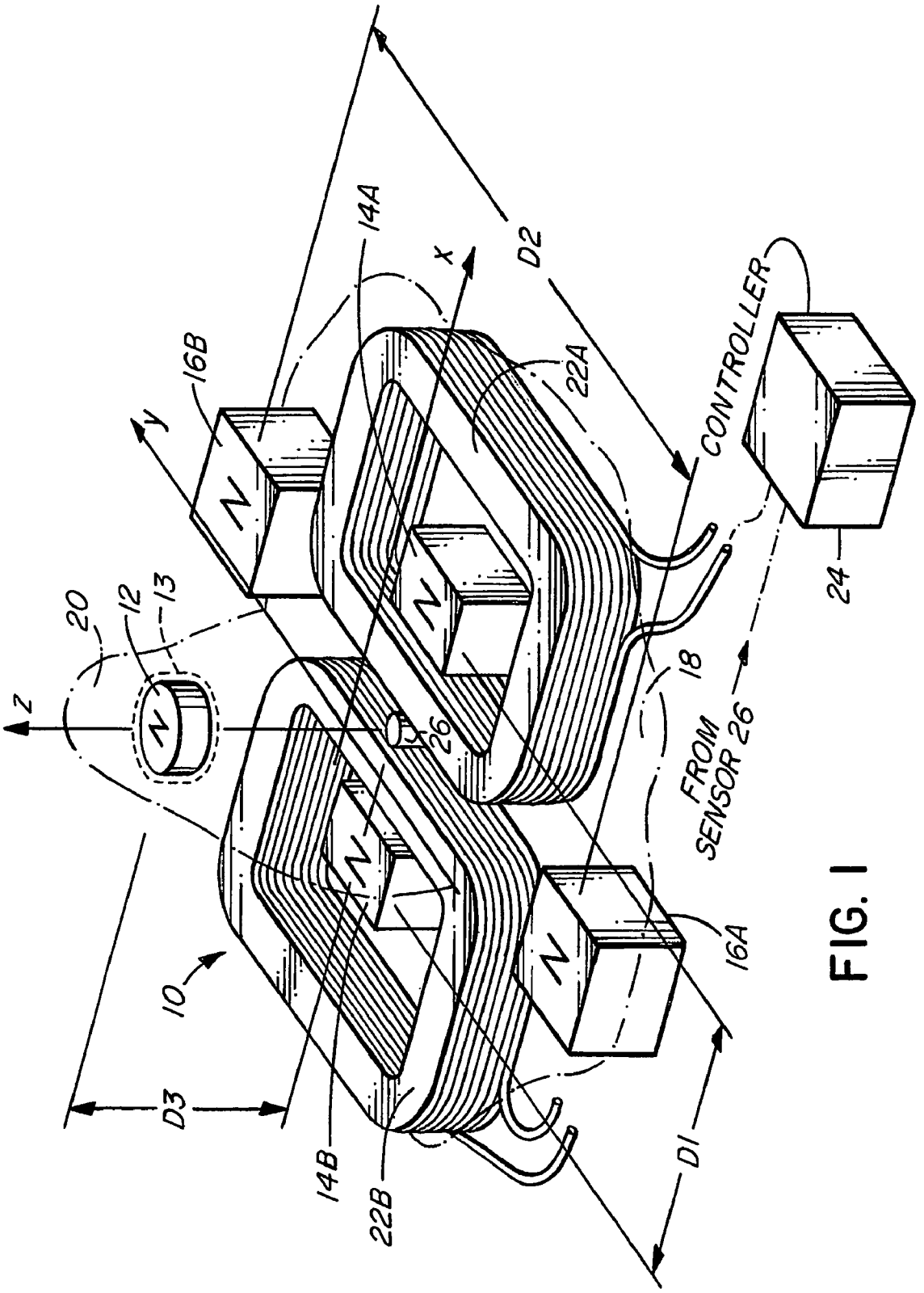

14A
X
D2
16B
Y
22A
CONTROLLER
20
12
13
Z
18
24
26
FROM SENSOR 26
16A
10
D3
14B
22B
D1

FIG. 1

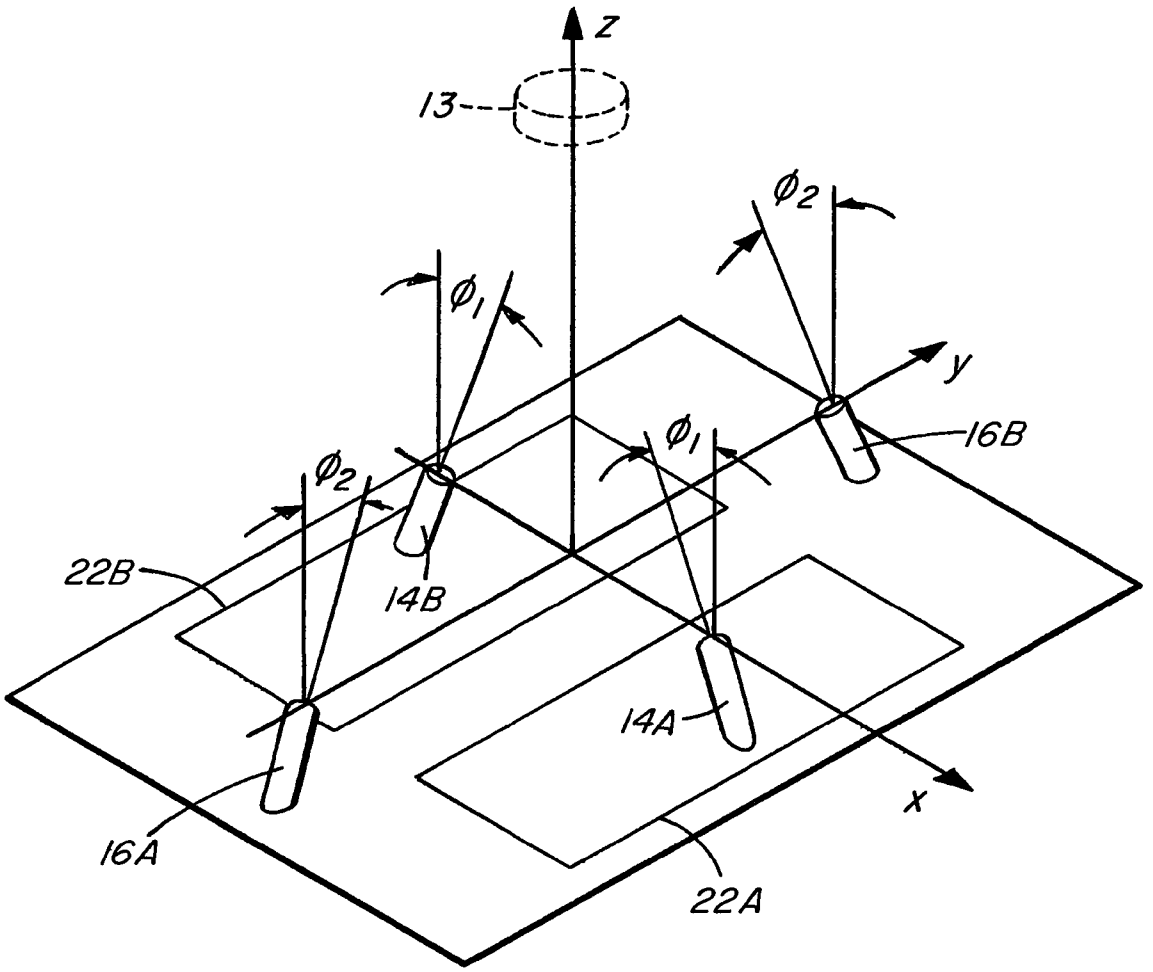


FIG. 1A

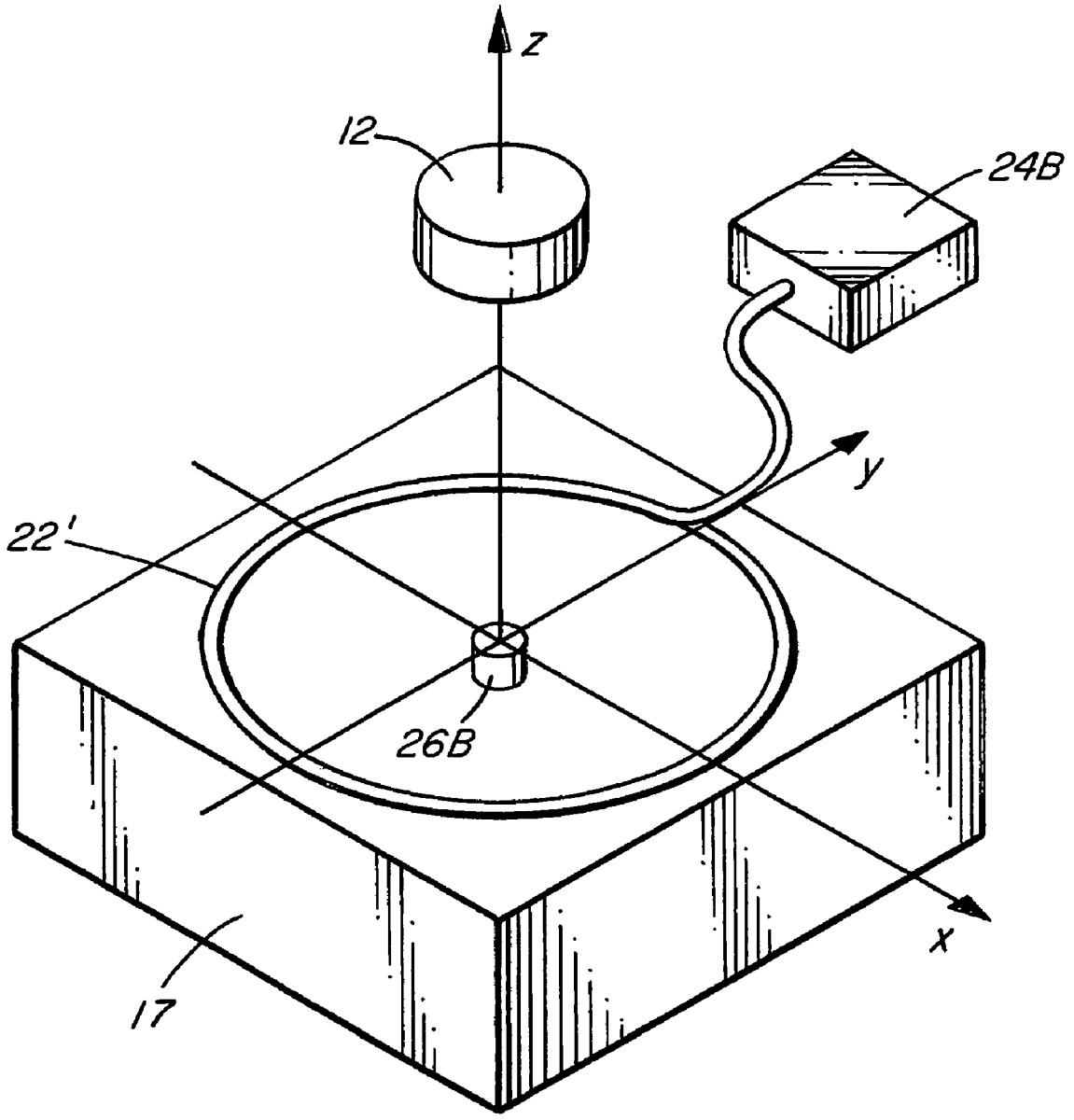


FIG. 1B

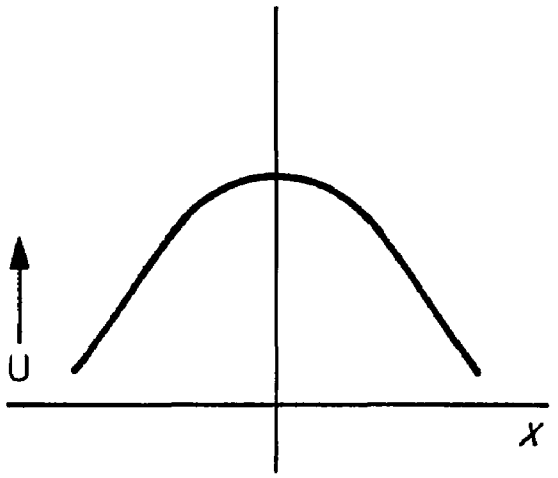


FIG. 2A

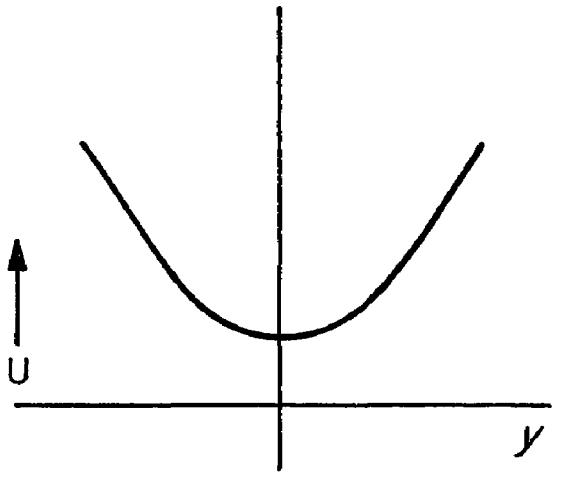


FIG. 2B

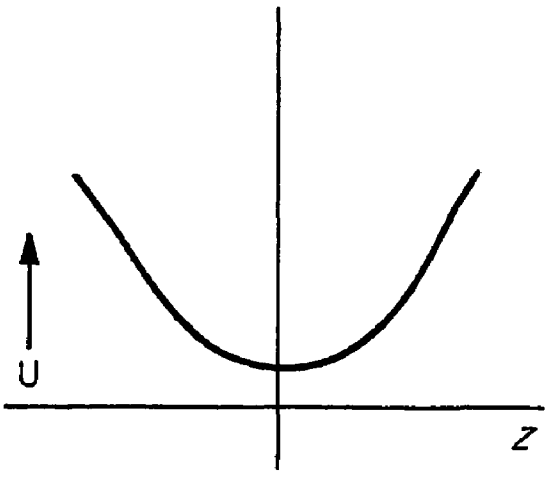


FIG. 2C

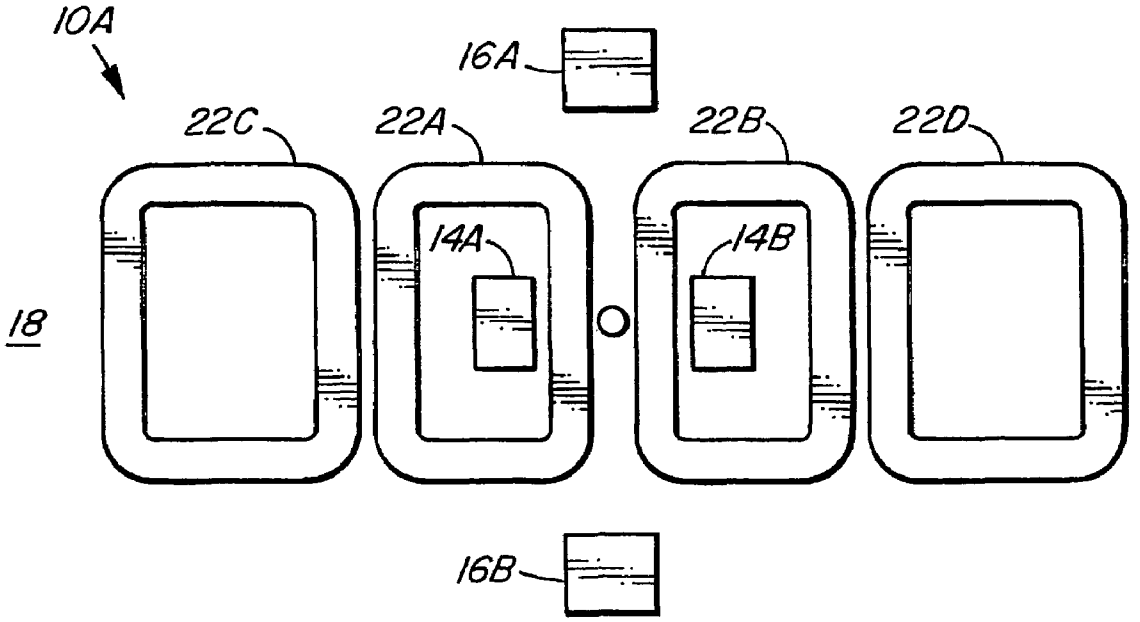

10A
16A
22C
22A
22B
22D
14A
14B
18
16B

FIG. 3

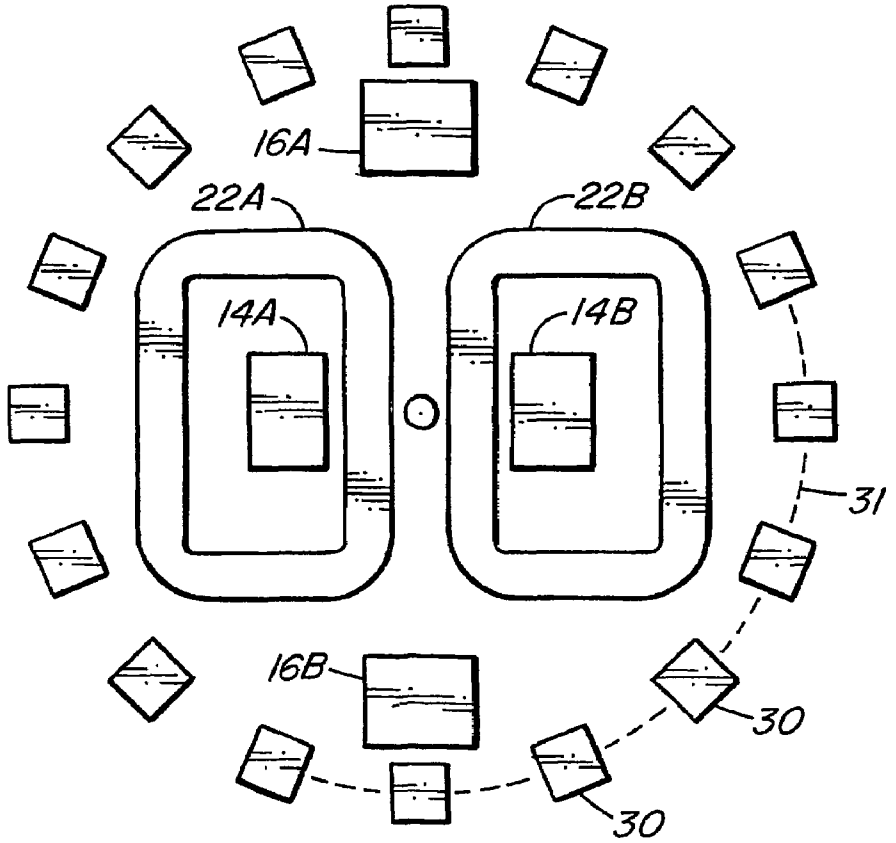

16A
22A
22B
14A
14B
31
16B
30
30

FIG. 4

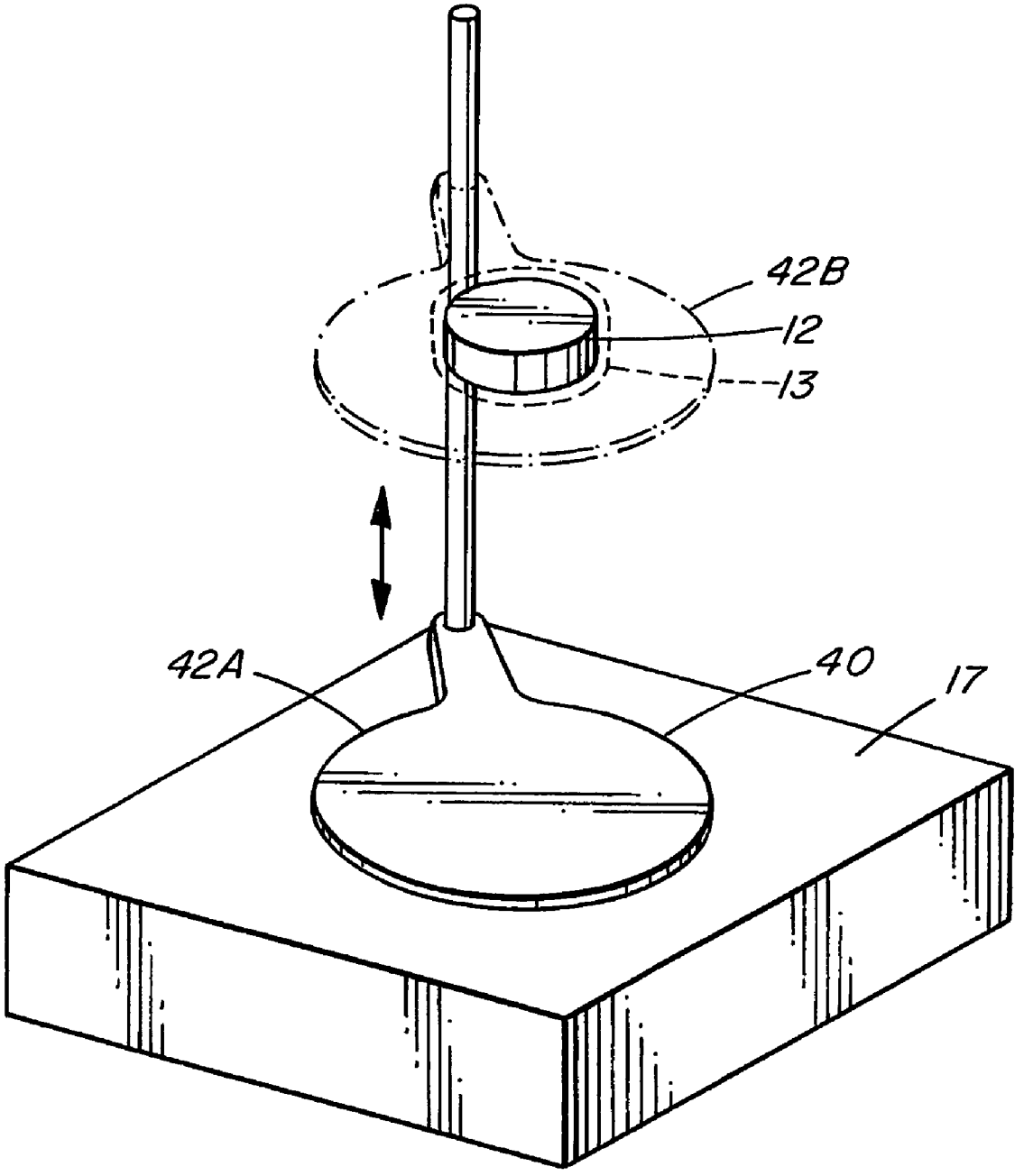


FIG. 5

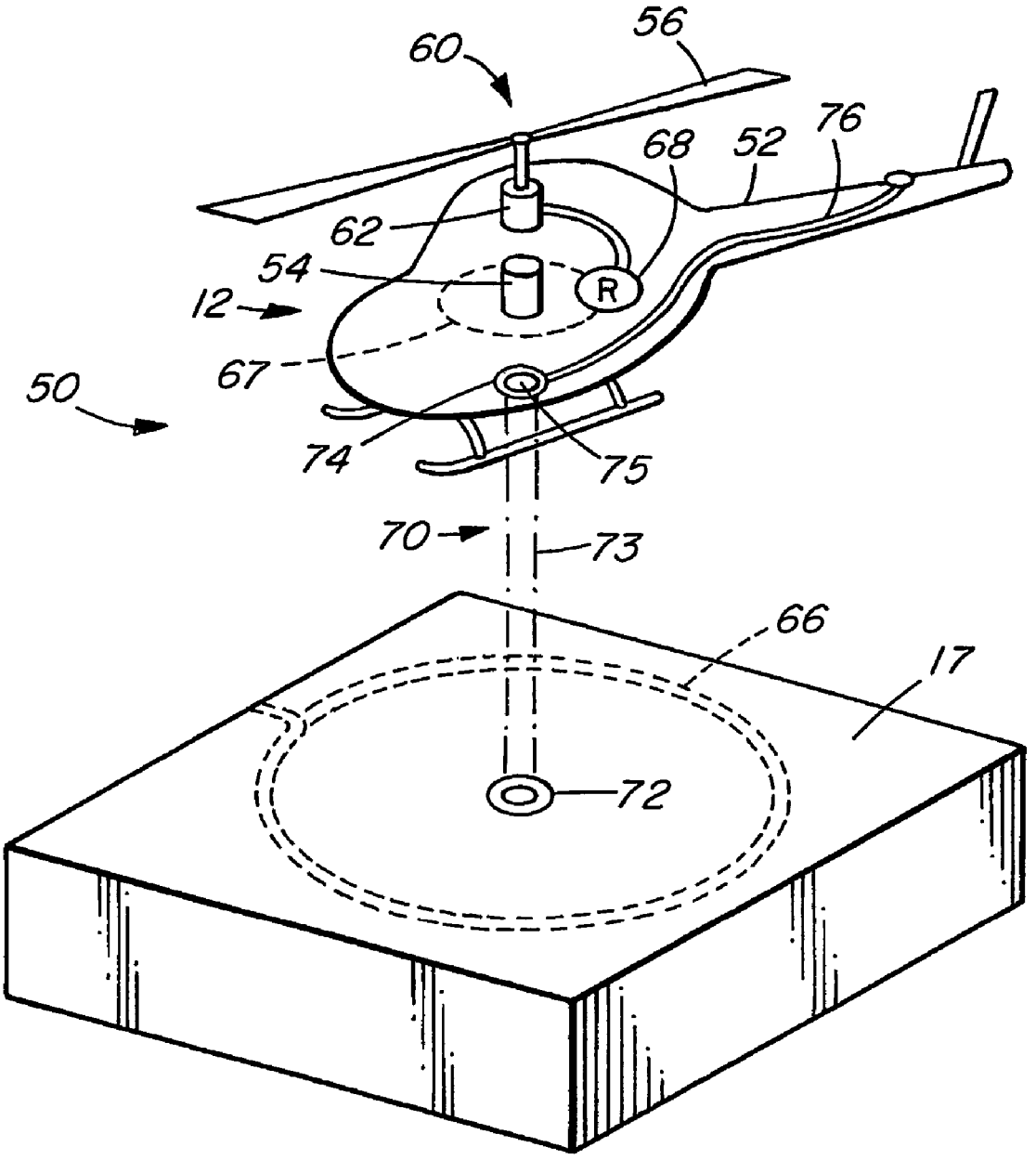


FIG. 6

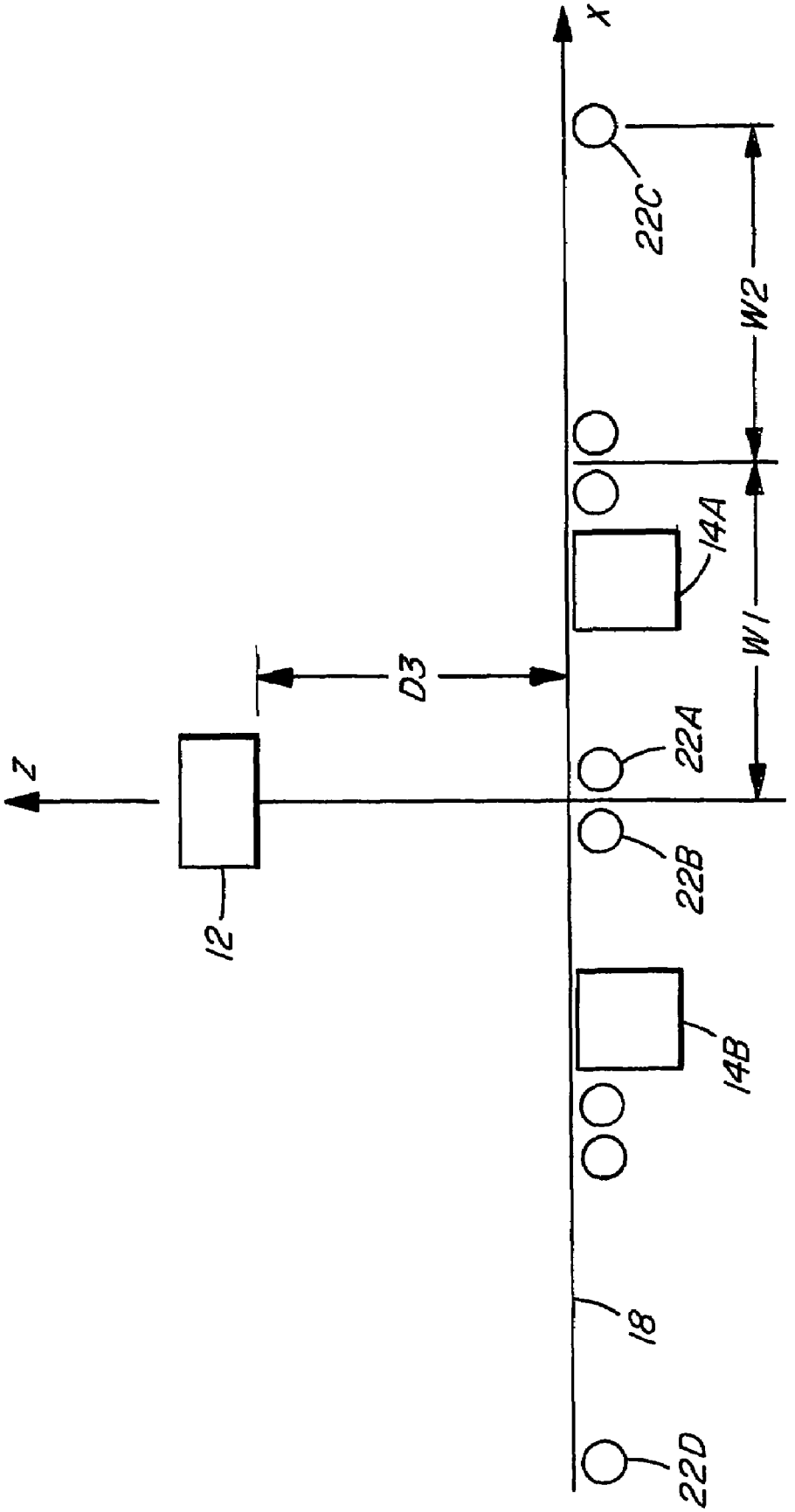


FIG. 7

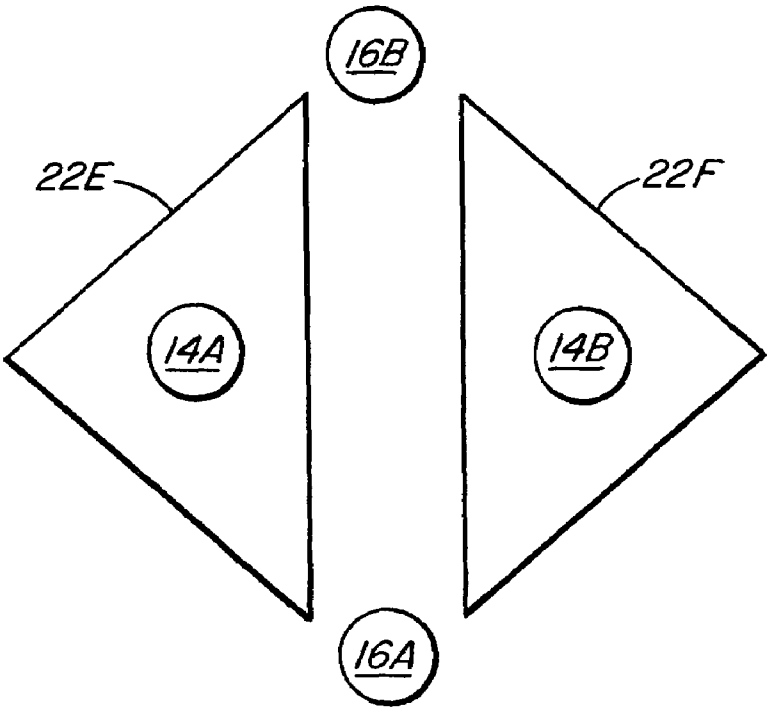


FIG. 8A

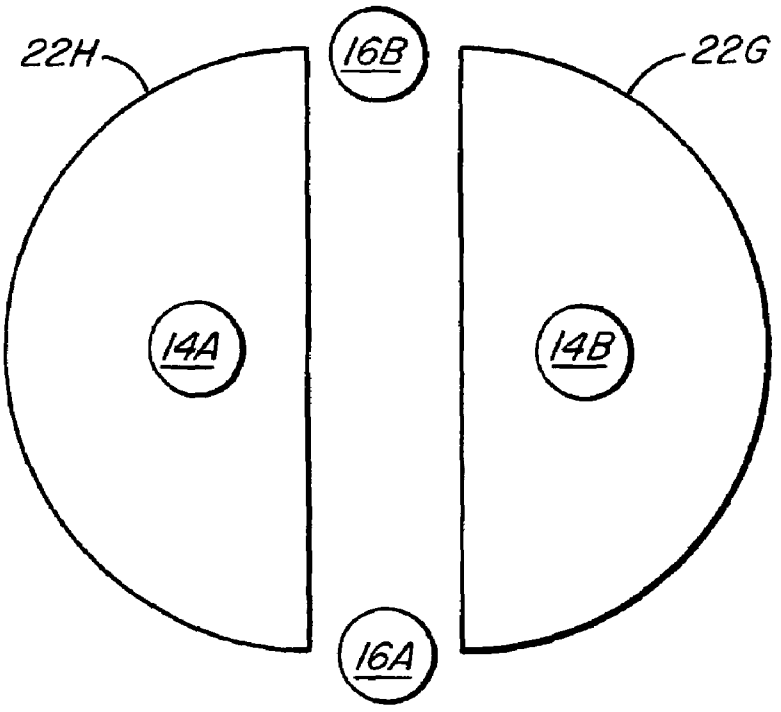


FIG. 8B

MAGNETIC LEVITATION APPARATUS

CROSS REFERENCE TO RELATED APPLICATION

This application claims priority from U.S. patent application No. 60/413,881 filed 27 Sep., 2002.

TECHNICAL FIELD

The invention relates to apparatus for levitating magnetic elements.

BACKGROUND

A levitated object is interesting to observe and can be useful in various applications. Magnetic fields provide one tool which can be used for levitating magnetic objects. According to Earnshaw's theorem, it is not possible to support a magnetic object in a stable manner using only static magnetic fields. One statement of Earnshaw's theorem is that a levitated magnet cannot be held in stable equilibrium by any combination of static magnetic or gravitational forces.

Whitehead, U.S. Pat. No. 5,168,183 discloses a magnetic levitation system in which an arrangement of magnets on one side of a separation plane can support a levitated magnetic element on an opposite side of the separation plane. The magnetic arrangement provides a static magnetic field such that, for displacements of the levitated element in directions parallel to a stability plane, the potential energy of the magnetic interaction between the levitated element and the static magnetic field increases. The magnetic arrangement includes a control system which controls a variable force, which may be a variable magnetic field, to stabilize the levitated element in a direction perpendicular to the stability plane.

The inventors have determined that the magnetic fields generated by the embodiments disclosed by Whitehead tend to apply torque to levitated magnetic elements. This is because the magnetic dipole of the levitated magnetic element aligns generally with the static magnetic field while the variable magnetic field used to control the position of the levitated magnetic element in the "unstable" direction is directed generally perpendicularly to the static magnetic field at the equilibrium location of the levitated magnetic element. The rotation caused by this torque can lead to combined torsional and translational oscillation of the levitated element. In some cases this adversely affects stable feedback control and thus the stability of the levitated magnetic element.

There is a need for magnetic levitation systems of the general type disclosed by Whitehead which have desirable operating characteristics, such as increased stability of the levitated magnetic element, and/or are simple in construction. For certain applications, there is a particular need for such levitation systems which incorporate a reduced amount of magnetic material and can be made at relatively low cost.

SUMMARY OF THE INVENTION

One aspect of the invention provides apparatus for levitating a magnetic element. The apparatus comprises at least two magnets arranged to generate a static magnetic field providing a position-dependent potential energy of interaction with a magnetic element. In certain embodiments the at least two magnets include four magnets arranged in a diamond pattern. The static magnetic field provides an equilibrium location wherein the potential energy decreases for displacements of the magnetic element away from the equilibrium location along an unstable axis and increases for displacements of the magnetic element away from the equilibrium location in any direction perpendicular to the unstable axis. The apparatus includes a position sensor generating a feedback signal indicative of the location of the magnetic element on the unstable axis, an electromagnet configured to generate a control magnetic field upon the passage of an electrical current through the electromagnet, the control magnetic field having a gradient with respect to displacements along the unstable axis at the equilibrium location, and, a controller connected to receive the feedback signal and to control the electrical current in the electromagnet to prevent the magnetic element from leaving a vicinity of the equilibrium location.

In some embodiments the electromagnet comprises at least two coils spaced along an axis parallel to the unstable axis. For example, the electromagnet may comprise four coils spaced along an axis parallel to the unstable axis wherein upon the passage of the electrical current through the four coils each of the four coils has a magnetic polarity opposite to the magnetic polarity of adjacent ones of the four coils.

A specific embodiment provides an apparatus wherein the at least two magnets comprise first and second magnets spaced apart from one another by a first distance, D**1**, in a direction parallel to the unstable axis and third and fourth magnets spaced apart from one another by a second distance, D**2**, in a direction transverse to the unstable axis, wherein D**1**<D**2**, each of the first and second magnets is equidistant from an axis of symmetry of the at least two magnets and each of the third and fourth magnets is equidistant from the axis of symmetry. Each of the first, second, third and fourth magnets may have a first magnetic pole facing toward the equilibrium location and a second magnetic pole facing away from the equilibrium location. The first magnetic poles of the first, second, third and fourth magnets may be substantially coplanar.

Another aspect of the invention provides apparatus for levitating a magnetic element. The apparatus comprises means for generating a static magnetic field providing a position-dependent potential energy of interaction with a magnetic element, the static magnetic field providing an equilibrium location wherein the potential energy decreases for displacements of the magnetic element away from the equilibrium location along an unstable axis and increases for displacements of the magnetic element away from the equilibrium location in any direction perpendicular to the unstable axis. The apparatus also comprises means for generating a feedback signal indicative of the location of the magnetic element on the unstable axis and control means for directing the magnetic element to the equilibrium location by providing a quadrupole control magnetic field at the equilibrium location in response to the feedback signal.

Further aspects of the invention and features of specific embodiments of the invention are described below.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate non-limiting embodiments of the invention,

FIG. **1** is a partially schematic view of a magnetic levitation system according to one embodiment of the invention;

FIGS. **1**A and **1**B are partially schematic views of magnetic levitation systems according to alternative embodiments of the invention.

FIGS. **2**A through **2**C are plots which show variation of magnetic potential energy with displacement from the equilibrium location of a levitated magnetic element along x, y and z axes of the system of FIG. **1** respectively;

FIG. **3** is a top plan view of a magnetic levitation system having control coils arranged to generate a quadrupole field at a equilibrium location;

FIG. **4** is a top plan view of a magnetic levitation system having magnets to improve stability of a levitated magnetic element against rotation;

FIG. **5** is a side view of a magnetic levitation system having a movable platform for supporting a magnetic element near an equilibrium location;

FIG. **6** shows mechanisms for illuminating and animating a levitated object;

FIG. **7** is a section taken in the x-z plane through control coils of an embodiment of the invention; and,

FIGS. **8**A and **8**B show coil geometries according to alternative embodiments of the invention.

DESCRIPTION

Throughout the following description, specific details are set forth in order to provide a more thorough understanding of the invention. However, the invention may be practiced without these particulars. In other instances, well known elements have not been shown or described in detail to avoid unnecessarily obscuring the invention. Accordingly, the specification and drawings are to be regarded in an illustrative, rather than a restrictive, sense.

FIG. **1** shows a magnetic levitation system **10** according to the invention. System **10** is shown levitating a magnetic element **12** at an equilibrium location **13**. Magnetic element **12** comprises a magnetic dipole or an array of magnetic dipoles. Magnetic element **12** may comprise a permanent magnet attached to a lightweight body to be levitated.

System **10** comprises a first pair of magnets **14** (individually **14**A and **14**B) spaced apart by a distance D**1** and a second pair of magnets **16** (individually **16**A and **16**B) spaced apart by a distance D**2** with D**2**>D**1**. In currently preferred embodiments of the invention, the ratio D**2**: D**1** is in the range of 1½:1 to 2:2.

Magnets **16**, which are further apart than magnets **14**, preferably have dipole moments larger than or equal to those of magnets **14**. The magnetic dipole moments of magnets **16** are preferably large enough to substantially counteract the undesirable curvature of the field lines of the magnetic field that would be present in the absence of magnets **16**, but not so large as to counteract the levitating field of the less-powerful magnets **14**, which has much higher gradients due to the proximity of magnets **14** to equilibrium location **13**. Preferably magnets **14**A and **14**B have the same magnetic strength as one another and magnets **16**A and **16**B have the same magnetic strength as one another. The strength, M_{14} of magnets **14** is preferably less than or equal to the strength, M_{16}, of magnets **16**. The ratio of M_{16}:M_{14} is in the range of 1:1 to 2:1 in some embodiments of the invention.

Magnets **14** are ideally arranged so that magnets **14**A and **14**B are disposed a first axis and magnets **16**A and **16**B are disposed on a second axis orthogonal to the first axis. In the following description, magnets **14** and **16** are all shown as being adjacent a plane **18**. A cartesian coordinate system having orthogonal x and y axes in plane **18** and a z axis normal to plane **18** has its origin located symmetrically relative to magnets **14** and **16**. The x axis extends through magnets **14** and they axis extends through magnets **16**. The z axis of the coordinate system of the illustrated system **10** provides a symmetry axis of system **10**. The z axis extends through equilibrium location **13**, which is a distance D**3** away from plane **18**.

While FIG. **1** shows the ideal case where magnets **14** and **16** are located on orthogonal axes, some deviation from this ideal arrangement is possible without departing from the invention. In the illustrated embodiment, magnets **14** and **16** are arranged in a diamond pattern. The establishment of a cartesian coordinate system is done only for convenience in describing the configuration of the illustrated apparatus. Other coordinate systems could be used.

Magnets **14** and **16** are preferably small in size compared to the distances between magnets **14**, **16** and equilibrium location **13** at which magnetic element **12** can be levitated by system **10**. In his case, each of magnets **14** and **16** produces a magnetic field at equilibrium location **13** substantially the same as a field which would be produced by a single magnetic dipole at the location of the magnet **14** or **16**.

In the embodiment illustrated in FIG. **1**, magnets **14** and **16** are all polarized in the same direction, which is parallel to the z axis. FIG. **1**A shows schematically an alternative embodiment of the invention wherein each of magnets **14** are inclined toward the z axis at an angle, ϕ_1, and each of magnets **16** are inclined toward the z axis at an angle, ϕ_2. In some embodiments $\phi_1=\phi_2$. In other embodiments ϕ_1 and ϕ_2 are different from one another. Inclining magnets **14** and/or **16** toward the z axis, as shown in FIG. **1**A, tends to gain some "stiffness" in the levitation of magnetic element **12** with respect to motion in one direction at the expense of reduced stability in one or more other directions.

Magnets **14** and **16** have poles of a first polarity (for example, N) oriented in a first direction (for example, the +z direction) and poles of a second polarity (for example S) oriented in a second direction opposite to the first direction (for example, the −z direction).

Any suitable magnets may be used for magnets **14** and **16**. Magnets **14** and **16** may, for example, comprise permanent magnets or electromagnets. Where system **10** is to be powered by batteries or another power supply that is limited in terms of total capacity or peak power, or in cases where it is desirable to minimize the electrical power consumption of system **10**, magnets **14** and **16** are preferably permanent magnets. In some embodiments, magnets **14** and **16** comprise NdFeB, Barium Ferrite, Samarium Cobalt or AlNiCo magnets. Magnets **14** and **16** may each comprise an array of magnetic dipoles.

In the illustrated embodiment, the poles of magnets **14** and **16** which are closest to equilibrium location **13** are co-planar and all lie immediately adjacent to a plane **18**. Magnets **14** and **16** may be mounted within a base **17** (See FIGS. **1**B, **5** and **6**). Magnets **14**, **16** and base **17** may be thin in the z direction. In some embodiments base **17** has a thickness significantly less than D**3**. For example, base **17** may have a thickness of ½×D**3** or less.

Magnets **14** and **16** generate a static magnetic field that supports magnetic element **12** in levitation at equilibrium location **13**. The static magnetic field has gradients such that a potential energy of the magnetic interaction between levitated magnetic element **12** and the static magnetic field increases for small displacements of levitated magnetic element **12** from equilibrium location **13** in directions parallel to a stability plane **20** (illustrated as the y-z plane in FIG. **1**).

FIGS. 2A, 2B and 2C illustrate the variation of magnetic potential energy with position of magnetic element 12 for displacements along x, y and z axes respectively. It can be seen that the magnetic potential energy increases for displacements away from equilibrium location 13 along either of they and z axes. Magnetic element 12 is therefore stable in respect of displacements along these axes. On the other hand, the magnetic potential energy decreases for displacements away from equilibrium location 13 in either direction along the x axis. Magnetic element 12 is therefore unstable in respect of displacements from equilibrium location 13 along the x axis.

System 10 includes control coils 22 (individually 22A and 22B) which generate a variable magnetic field under the control of a controller 24 (FIG. 1). When magnetic element 12 moves away from its levitated equilibrium position 13, controller 24 adjusts flow(s) of electrical current in the control coils to cause control coils 22 to generate a magnetic field that results in a force being applied to magnetic element 12. The force pushes magnetic element 12 in a selected direction along the unstable x axis. The variable magnetic field generated by the passage of electrical current in the control coils stabilizes levitated magnetic element 12 with respect to motions in the direction of the x axis. In the embodiment illustrated in FIG. 1, coils 22A, and 22B are adjacent to one another, have their centers spaced apart along the x axis, and each of coils 22 surrounds one of magnets 14.

A position sensor 26 provides a signal representative of the displacement of levitated magnetic element 12 on the unstable x axis to controller 24. In the illustrated embodiment, sensor 26 is located at the center of symmetry of system 10 directly below equilibrium location 13. Position sensor 26 may comprise a Hall effect sensor, for example. A Hall effect sensor may be oriented to detect the magnetic field intensity from levitated magnetic element 12 in a direction parallel to the x axis. When magnetic element 12 is located at equilibrium location 13 then the magnetic dipole of magnetic element 12 is aligned with the static magnetic field, which is oriented parallel to the z axis. The magnetic dipole of magnetic element 12 yields no net magnetic field component in a direction parallel to the x axis at the location of sensor 26. If magnetic element 12 moves along the unstable x axis in either direction then the field from its magnetic dipole, as detected at sensor 26, has a non-zero component in the x direction which increases with increasing displacement of magnetic element 12 from equilibrium location 13. Thus, the signal output by a Hall effect sensor 26 can be used to provide feedback to controller 24 regarding the position of magnetic element 12 along the unstable x axis.

Controller 24 adjusts current in coils 22 to maintain levitated magnetic element 12 at equilibrium location 13. Controller 24 may comprise any suitable control technology including a suitably programmed data processor such as a computer, programmable controller, or digital signal processor, or a suitable analog or digital feedback control circuit.

The distance D3 between equilibrium location 13 at which magnetic element 12 can be stably levitated and the plane 18 adjacent to magnets 14 and 16 may be varied by adjusting distance D1 between magnets 14A and 14B. Decreasing distance D1 slightly while magnetic element 12 is being levitated causes distance D3 to decrease while increasing the stability of magnetic element 12 with respect to displacements from equilibrium location 13 in stability plane 20 (i.e. the y-z plane in FIG. 1). Increasing distance D1 slightly while magnetic element 12 is being levitated causes distance D3 to increase while decreasing the stability of magnetic element 12 with respect to displacements from equilibrium location 13 in stability plane 20.

Preferably equilibrium location 13 is a position such that the static magnetic field of magnets 14 and 16 provides sufficient force to counteract the force of gravity on magnetic element 12 at equilibrium location 13 in the absence of current flowing in coils 22. Magnetic element 12 is unstable in the x direction. Coils 22 are operated to counteract any movement in the x direction of magnetic element 12 away from equilibrium location 13. In such embodiments it is only necessary to cause current to flow in coils 22 when magnetic element 12 has moved or is moving away from equilibrium location 13. This makes it possible to minimize the electrical power expenditure required to stabilize magnetic element 12 at equilibrium location 13.

Control coils 22 are arranged so that they can be operated to provide a magnetic field gradient (dBz/dx) near equilibrium location 13 sufficient to control the position of magnetic element 12 on the unstable x axis. The dimensions and locations of coils 22 may advantageously be chosen so that the magnitude of the magnetic field produced by coils 22 is very small in the vicinity of equilibrium location 13. This permits stabilization of magnetic element 12 without introducing significant transverse magnetic field components at the location of magnetic element 12 which would tend to rotate magnetic element 12. In practice, it is desirable that the components of the magnetic field from coils 22 in the x, y and z directions be as small as practical at equilibrium location 13 while having a gradient (dBz/dx) in the x direction large enough to provide sufficient force to control the position of magnetic element 12 on the x axis.

FIG. 3 illustrates a system 10A having one configuration of control coils 22 which minimizes the magnetic field from coils 22 in the vicinity of equilibrium location 13. The same reference numbers are used to indicate parts of system 10A which are also found in system 10 of FIG. 1. System 10A has four coils 22, coils 22A, 22B, 22C, and 22D. Coils 22A through 22D are rectangular coils arranged parallel to plane 18 and parallel to one another. The long sides of coils 22A to 22D extend parallel to the y axis and transversely to the unstable x axis. Coils 22A through 22D are arrayed symmetrically along the x axis. Magnets 14A and 14B may be within coils 22A and 22B respectively, as shown. Coils 22A through 22D are located symmetrically with respect to the y-z stability plane. Ideally coils 22A and 22B are close together, coils 22A and 22C are close together and coils 22B and 22D are close together. Coils 22C and 22D are preferably wider than coils 22A and 22B in their dimensions parallel to the x axis. In the illustrated embodiment, coil 22A has the same dimensions as coil 22B and coil 22C has the same dimensions as coil 22D.

It is desirable that at least those components of the magnetic fields generated by coils 22 which are parallel to plane 18 substantially cancel one another, at least in the vicinity of equilibrium location 13. This result may be produced by suitably choosing the dimensions of coils 22 and passing appropriate electric current(s) through coils 22 in appropriate senses. Electrical current passes through inner coils 22A and 22B in opposite senses to generate a stabilizing magnetic force on magnet 12. If the current passes through coil 22A in a clockwise sense, current must pass counterclockwise through coil 22B. At the same time, the current flow in coil 22C is counterclockwise and the current flow in coil 22D is clockwise. This creates a stabilizing magnetic field which applies force to urge magnetic element 12 in one direction along the unstable x axis. To create a

stabilizing magnetic field which applies force to urge magnetic element **12** in the opposite direction along the unstable x axis, the sense in which current flows in each of coils **22** can be reversed.

The arrangement of coils **22** shown in FIG. **3** produces a magnetic quadrupole field at equilibrium location **13** when coils **22** have equal numbers of windings, suitable dimensions, and carry equal electrical currents flowing in the correct sense in each coil. A magnetic quadrupole is a point in space where the magnitude of a magnetic field is zero while the gradients of the magnetic field are linear and symmetric about the point. In this case, coils **22** cause a stabilizing magnetic force to be applied to magnetic element **12**. The magnitude of the stabilizing force applied to magnetic element **12** is proportional to the magnitude of the gradient dBz/dx of the magnetic field at the location of magnetic element **12**.

FIG. **7** is a section taken in the x-z plane through coils **22**. For coils **22** to produce a quadrupole field at equilibrium location **13** it is desirable that coils **22**A and **22**B have equal widths W**1**, coils **22**C and **22**D have equal widths W**2** and that W**1** be related to W**2** and the distance D**3** by W**1**=D**3** and W**2**≧D**3**. All of coils **22** may have the same length. The length of each coil **22** in the direction transverse to the unstable x axis is greater than its width.

Controller **24** preferably inhibits the operation of system **10** in case magnetic element **12** is not detected by sensor **26** as being in the vicinity of equilibrium location **13**. For example, if magnetic element **12** crashes it is desirable to prevent controller **24** from attempting to correct the position of magnetic element **12** by passing electrical current through coils **22**. This would waste energy, could cause coils **22** to overheat, and in an extreme case could damage the control circuits which supply power to coils **22**. Controller **24** may be configured to switch to an inactive mode whenever the signal from sensor **26** indicates that magnetic element **12** is not within a desired distance of equilibrium location **13**. Controller **24** may be configured to remain in the inactive mode until reset. System **10** may include a reset switch which can be operated by a user to reset controller **24**.

In some cases it can be desirable to provide additional magnets which add to the strength of the static magnetic field at equilibrium location **13**. The stability of magnetic element **12** against overturning moments increases with the strength of the static magnetic field at equilibrium location **13**. This is because the magnetic dipole of magnetic element **12** tends to align itself with the surrounding magnetic field. If the magnetic dipole of magnetic element **12** becomes misaligned with the magnetic field then magnetic element **12** experiences a corrective torque. The magnitude of the corrective torque is proportional to the strength of the magnetic field at the location of magnetic element **12**.

FIG. **4** shows an arrangement of additional magnets **30** which increases the strength of the magnetic field at equilibrium location **13** but does not adversely affect the magnetic field gradients which create the forces used to maintain magnetic element **12** at equilibrium location **13**. Additional magnets **30** are arranged in a ring **31**. Each additional magnet **30** provides a magnetic dipole oriented in the same sense as magnets **14**.

Ring **31** lies in plane **18** or in a plane parallel to plane **18**. Equilibrium location **13** lies on a line extending perpendicular to the plane of ring **31** from the center of ring **31**. The radius of ring **31** is chosen so that the z component of the magnetic field produced by magnets **30** has substantially no gradient in the z direction at equilibrium location **13** (i.e. at equilibrium location **13**, dB(30)z/dz=0) where B(30)z is the z component of the magnetic field produced by magnets **30**. In this context, "substantially no gradient" means a gradient which is at least significantly less than, preferably less than 25% of and most preferably less than 7% of, the gradient of the static magnetic field produced by magnets **14** and **16** which cause magnetic element **12** to levitate at equilibrium location **13**. By virtue of symmetry of the magnets in ring **31** about the z axis, there are no net horizontal components of the magnetic field produced by magnets **30** at equilibrium location **13** that would cause magnetic element **12** to align itself in any direction but parallel to the z axis.

System **10** may be started by initially supporting magnetic element **12** in the vicinity of equilibrium location **13**, engaging controller **24** and then removing whatever support is used to provide initial support to magnetic element **12**. For example, system **10** may include a non-magnetic support **40** which is movable relative to magnets **14** and **16** between a lowered position **42**A and a raised position **42**B as shown in FIG. **5**. When support **40** is in its raised position **42**B it supports magnetic element **12** at equilibrium location **13**. After system **10** is operating to maintain magnetic element **12** at equilibrium location **13**, support **40** can be lowered to position **42**A.

Support **40** may comprise an arm, a table, a column, or the like. Support **40** is movable between a first position in which it supports magnetic element **12** at or near equilibrium location **13** and a second position in which it is out of the way of equilibrium location **13**. Any suitable mechanism may be provided to enable support **40** to move between the first and second positions. The mechanism may comprise, for example, one or more hinges, pivots, sliding members, flexible members, or the like.

As shown in FIG. **1**B, system **10** may optionally include one or more secondary electromagnets **22'**. Secondary electromagnets **22'** may be used to further stabilize magnetic element **12**. For instance, an electromagnet that is symmetric about the z axis and is located parallel to plane **18** can generate a magnetic field gradient parallel to the z axis that augments the static magnetic field from magnets **14** and **16**. This magnetic field gradient will generate a force on the magnetic element **12** in a direction parallel to the z axis. The magnitude and sense of the force is controlled by the electric current flowing in secondary electromagnet **22'**. A secondary sensor **26**B oriented to detect motion of the magnetic element along the z axis provides feedback to a secondary controller **24**B (which could be an independent control pathway provided by the same hardware/software used to provide controller **24** or could be a separate independent controller). Controller **24**B controls the electric current flow in secondary electromagnet **22'**. The secondary electromagnet system may be used to dampen vibration of magnetic element **12** along the z axis or to cause magnetic element **12** to move in the +z or −z direction about equilibrium location **13**. By repeatedly reversing the flow of current in secondary electromagnet **22'** at an appropriate rate, controller **24**B can cause magnetic element **12** to oscillate about equilibrium location **13** along the z axis.

Electromagnets in other orientations with appropriate feedback sensors may be provided in conjunction with suitable controllers to provide forces on the magnetic element **12** along they axis or to provide magnetic torques on magnetic element **12**. In this manner, the levitated element can be steered around the equilibrium location to a limited degree or made to vibrate in some direction.

System **10** may include mechanisms to animate or illuminate magnetic element **12**. FIG. **6** shows a novelty toy **50**, which includes a mechanism for animating magnetic ele-

ment **12**, and a system for illuminating magnetic element **12**. FIG. **6** omits details of the mechanism for levitating magnetic element **12** for clarity. The levitation mechanism may be enclosed within base **17**.

In toy **50**, magnetic element **12** comprises a lightweight shell **52** resembling the body of a helicopter. A permanent magnet **54** is affixed within shell **52**. Magnet **54** interacts with a levitation system, as described above, to levitate magnetic element **12** at an equilibrium location. Toy **50** includes an animation mechanism **60**. Animation mechanism **60** comprises a small electric motor **62** which drives a rotor **56**. Motor **62** is powered by electrical power supplied by way of a high frequency coupling system. The coupling system may comprise an air core transformer. A transmitting coil **66** mounted in base **17** is excited with high frequency (e.g. radio frequency) electrical signals. A signal emitted by transmitting coil **66** is coupled to a receiving coil **67** in magnetic element **12**. This induces electrical currents in receiving coil **67**. The electrical currents are rectified by a rectifier circuit **68** to produce electricity which drives motor **62**. Electricity from rectifier circuit **68** could be used to power electrical devices other than or in addition to motor **62**. For example, the electricity could be used to operate small lamps (which could be, for example, light-emitting diodes (LEDs).

Toy **50** also includes an illumination system **70**. Illumination system **70** comprises a high intensity light source **72** in base **17**. Light source **72** generates a beam **73** of light. Beam **73** illuminates a light receptor **74** on magnetic element **12**. In the illustrated embodiment, light receptor **74** comprises a lens **75** which focuses light from beam **73** into a bundle of optical fibers **76**. Optical fibers **76** extend to locations on shell **52** corresponding to navigation lights and the like. Beam **73** may be tightly confined so that it is not readily apparent to a person observing toy **50**. Mirrors, diffusers or other optical elements may be used to direct light from light receptor **74** to illuminate surface features of magnetic element **12** instead of or in addition to optical fibers **76**.

Where a component (e.g. a magnet, assembly, device, circuit, etc.) is referred to above, unless otherwise indicated, reference to that component (including a reference to a "means") should be interpreted as including as equivalents of that component any component which performs the function of the described component (i.e., that is functionally equivalent), including components which are not structurally equivalent to the disclosed structure which performs the function in the illustrated exemplary embodiments of the invention.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. For example:

- In the illustrated embodiments, the magnetic dipole moments of magnets **14** and **16** are parallel to one another. In some embodiments of the invention, magnets **14** and/or **16** are oriented so that their magnetic dipole moments lie at acute angles to plane **18**.
- In the illustrated embodiment, the uppermost poles of magnets **14** and **16** are co-planar and all lie adjacent to a plane **18**. Magnets **14** and **16** are not necessarily co-planar.
- In the illustrated embodiments, the "N" poles of magnets **14** and **16** face equilibrium location **13**. The polarity of magnets **14** and **16** could be reversed so that "S" poles of magnets **14** and **16** face equilibrium location **13**.
- Control coils **22** are not necessarily formed of a plurality of discrete coils. A single winding may be arranged to provide a magnetic field substantially the same as the magnetic field provided by a number of discrete coils.
- Additional rings of magnetic dipoles concentric with ring **31** may be provided. Since it is preferred that the ring (s) produce a magnetic field for which dB(30)z/dz=0 at equilibrium location **13**, where there are rings of different diameters, each ring is preferably located at a different distance from equilibrium location **13** to keep dB(30)z/dz=0.
- Ring **31** may comprise one or more ring magnets instead of discrete dipoles.
- Magnets **14** and/or magnets **16** could be replaced by an arrangement of symmetrically arranged smaller magnets which produce a similar magnetic field. However, it is generally desirable to use fewer discrete magnets, rather than more so as to minimize the space taken up by magnets.
- While coils **22** have been illustrated as being rectangular, other coil shapes could also be used to generate a stabilizing magnetic force on magnetic element **12**. For example, the coils could be triangular like coils **22**E and **22**F of FIG. **8**A or semicircular like coils **22**G and **22**H of FIG. **8**B.
- Any suitable non-contact sensor may be used for sensor **26**. Sensor **26** could, for example, comprise a suitable optical, capacitative, or other sensor. Sensor **26** may detect the position of magnetic element **12** along the unstable axis in any suitable manner. In preferred embodiments, sensor **26** is of a type that can detect motion of magnetic element **12** along the unstable axis from a location that is removed from equilibrium location **13** by a distance equal to the distance between plane **18** and equilibrium location **13**.

Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

What is claimed is:

1. Apparatus for levitating a magnetic element, comprising:

at least three magnets defining a common plane and arranged to generate a static magnetic field providing a position-dependent potential energy of interaction with a magnetic element located above the plane, the static magnetic field defining an elongated equilibrium location wherein the potential energy decreases for displacements of the magnetic element away from the equilibrium location along an unstable axis substantially orthogonal to the longitudinal axis of the elongated equilibrium location and increases for displacements of the magnetic element away from the equilibrium location in any direction along the longitudinal axis;

a position sensor generating a feedback signal indicative of the location of the magnetic element on the unstable axis;

an electromagnet configured to generate a control magnetic field upon the passage of an electrical current through the electromagnet, the control magnetic field having a gradient with respect to displacements along the unstable axis at the equilibrium location; and

a controller connected to receive the feedback signal and to control the electrical current in the electromagnet to prevent the magnetic element from leaving a vicinity of the equilibrium location.

2. An apparatus according to claim 1 wherein the electromagnet comprises at least two coils spaced along an axis parallel to the unstable axis.

3. An apparatus according to claim 2 wherein the at least two coils are rectangular coils having long sides extending transversely to the unstable axis.

4. An apparatus according to claim 2 wherein the electromagnet comprises four coils spaced along an axis parallel to the unstable axis wherein upon the passage of the electrical current through the four coils each of the four coils has a magnetic polarity opposite to the magnetic polarity of adjacent ones of the four coils.

5. An apparatus according to claim 2 wherein the electromagnet comprises four coils spaced along an axis parallel to the unstable axis, the four coils comprising first and second rectangular coils located between third and fourth rectangular coils wherein, upon the passage of the electrical current through the first through fourth coils, a component of a magnetic field produced by the first and second coils at the equilibrium located is cancelled by a magnetic field produced by the third and fourth coils.

6. An apparatus according to claim 3 wherein the coils of the electromagnet are substantially coplanar with the coplanar magnets.

7. An apparatus according to claim 1 wherein the electromagnet is configured to generate a quadrupole magnetic field at the equilibrium location upon the passage of the electrical current.

8. An apparatus according to claim 1 wherein the at least three magnets comprise first, second, third and fourth magnets arranged in a diamond pattern.

9. An apparatus according to claim 8 wherein the third and fourth magnets are stronger than the first and second magnets.

10. An apparatus according to claim 8 wherein the four magnets comprise first and second magnets spaced apart from one another by a first distance, D1 in a direction parallel to the unstable axis and third and fourth magnets spaced apart from one another by a second distance, D2, in a direction along the longitudinal axis, wherein D1<D2, each of the first and second magnets is equidistant from the longitudinal axis and each of the third and fourth magnets is equidistant from the unstable axis.

11. An apparatus according to claim 10 wherein each of the first and second magnets is equidistant from each of the third and fourth magnets.

12. An apparatus according to claim 10 wherein each of the first, second, third and fourth magnets has a first magnetic pole facing toward the equilibrium location and a second magnetic pole facing away from the equilibrium location and the first magnetic poles of the first, second, third and fourth magnets are substantially coplanar.

13. An apparatus according to claim 12 wherein the first magnetic poles of the first, second, third and fourth magnets are substantially coplanar adjacent to a plane extending perpendicular to the symmetry axis.

14. An apparatus according to claim 13 wherein the electromagnet comprises at least two coils lying parallel to and adjacent the plane.

15. An apparatus according to claim 1 wherein the at least three magnets comprise permanent magnets.

16. An apparatus according to claim 1 wherein the at least three magnets are all permanent magnets.

17. An apparatus according to claim 10 wherein the electromagnet comprises at least two coils spaced along an axis parallel to the unstable axis and the first one of the at least two coils extends around the first magnet and a second one of the at least two coils extends around the second magnet.

18. An apparatus according to claim 17 where the at least two coils of the electromagnet each have width W1 along the axis parallel t the unstable axis equal to an equilibrium height D3, wherein the equilibrium height D3 is a distance between the equilibrium position and a plane passing th rough the at least two coils.

19. an apparatus according to claim 18 comprising third and fourth coils positioned along the axis parallel to the unstable axis on either side of and adjacent to the first and second coils, the third and fourth coils having the widths W2 at least equal to width W1 of the first and second coils.

20. An apparatus according to claim 17 wherein the third and fourth permanent magnets are both located outside of any of the at least two coils.

21. An apparatus according to claim 17 wherein the at least two coils comprise rectangular coils.

22. An apparatus according to claim 17 wherein the at least two coils comprise semi-circular coils.

23. An apparatus according to claim 17 wherein the at least two cols comprise triangular coils.

24. An apparatus according to claim 12 wherein the first, second, third and fourth magnets are positioned such that a line passing through the first and second magnetic poles of each of the first, second, third and fourth magnets intersects and forms an acute angle with the axis of symmetry.

25. An apparatus according to claim 8 wherein the first, second, third and fourth permanent magnets are permanent magnets selected from a group consisting of NdFeB, Barium Ferrite, Samarium Cobalt and AlNiCo magnets.

26. An apparatus according to claim 1 comprising an arrangement of field reinforcing magnets positioned to generate a magnetic field which has substantially no gradient at the equilibrium location and which augments the static magnetic field near the equilibrium position.

27. An apparatus according to claim 26 wherein the arrangement of field reinforcing magnets comprises at least three magnetic dipoles spaced apart to form a ring.

28. An apparatus according to claim 27 wherein the at least three magnetic dipoles comprise at least three permanent magnets spaced apart to form the ring.

29. An apparatus according to claim 27 wherein the arrangement of field reinforcing magnets comprises a secondary electromagnet.

30. An apparatus according to claim 29 comprising a secondary controller for controlling an electrical current through the secondary electromagnet and a secondary sensor for generating a feedback signal indicative of a distance of the magnetic element from a plane passing through the secondary electromagnet.

31. An apparatus according to claim 1 comprising a transmitting coil connected to a source of alternating current having a frequency in excess of 10 kHz wherein the magnet element comprises a receiving coil and an electrical device powered by electrical current induced in the receiving coil.

32. An apparatus according to claim 31 wherein the electrical device comprises a rectifier connected to supply direct current to a motor.

33. An apparatus according to claim 31 wherein the electrical device comprises a lamp.

34. An apparatus according to claim 1 comprising a light source oriented to direct a beam of light at a light receptor on the magnetic element wherein the magnetic element

comprises an optical system for directing light from the light receptor to one or more visible locations on the magnetic element.

35. An application according to claim **1** comprising a support moveable between a first position in which the support supports the magnetic element approximately at the equilibrium location, and a second position in which the support is out of the way of the equilibrium location.

36. An apparatus according to claim **1** comprising a secondary electromagnet disposed to apply a force to the levitated magnetic element.

37. Apparatus for levitating a magnetic element, the apparatus comprising:

at least three magnets defining a plane and arranged to generate a static magnetic field providing a position-dependent potential energy of interaction with a magnetic element located above the plane, the static magnetic field providing an equilibrium location wherein the potential energy decreases for displacements of the magnetic element away from the equilibrium location along an unstable axis and increases for displacements of the magnetic element away from the equilibrium location in any direction perpendicular to the unstable axis, the at least two magnets comprising first and second magnets spaced apart from one another by a first distance, D**1**, in a direction parallel to the unstable axis and third and fourth magnets spaced apart from one another by a second distance, D**2**, in a direction perpendicular to the unstable axis, wherein D**1**<D**2** and each of the first and second magnets and each of the third and fourth magnets is equidistant from the axis of symmetry;

a position sensor generating a feedback signal indicative of the location of the magnetic element on the unstable axis; and

a controller connected to receive the feedback signal and to control a means for applying a controllable force to the magnetic element to direct the magnetic element to the equilibrium location.

38. The apparatus of claim **37** wherein said magnets are smaller in size than the shortest distance between said magnets.

39. The apparatus of claim **37** wherein said means for applying a controllable force is located in the same plane as the at least three co-planar static field magnets.

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